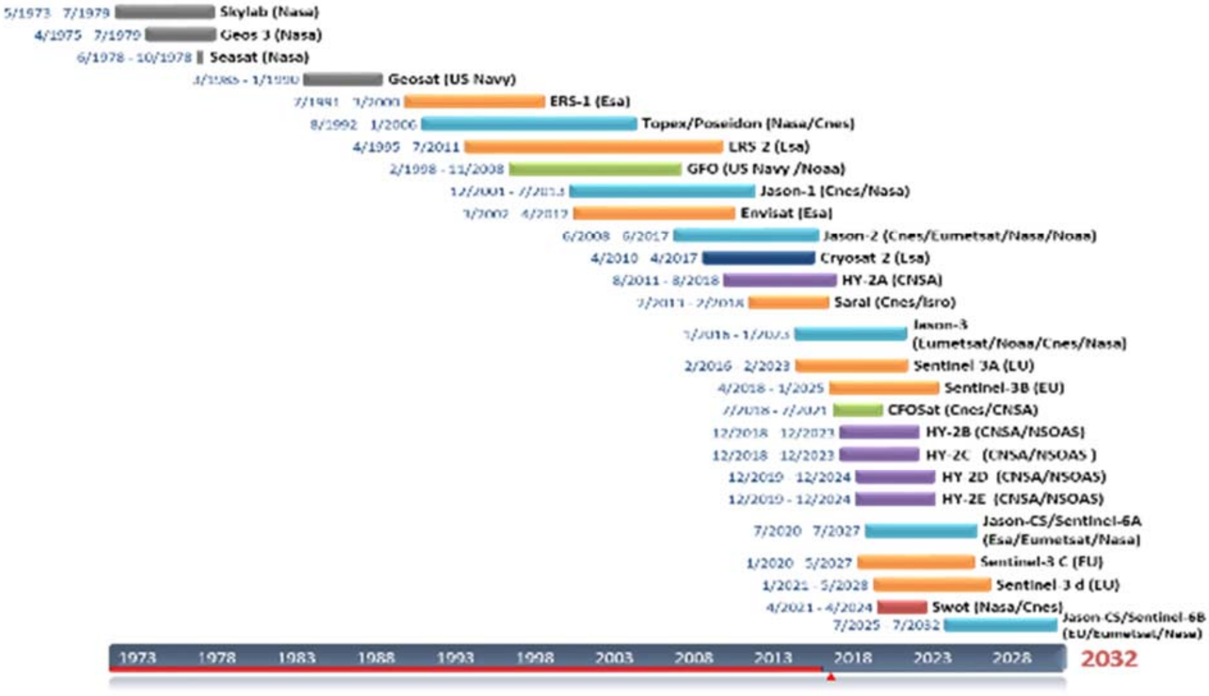
# How to use altimetry for hydrology?

Satellite radar altimetry was designed and developed in the 1970s to study the spatial and temporal variability of ocean height. Nowadays, radar altimeters measure the instantaneous height of the ocean surface below the vertical position of the satellite ("at nadir"), with an accuracy of a few centimetres. Unlike passive measuring systems that use radiation emitted by the Sun or the Earth, radar instruments are active systems that use their own radiation source, which offers several advantages: measurement accuracy, penetration power, use both by day and by night, etc. In addition, the wavelengths employed mean radar can be used in all weather conditions (measurements can be taken through clouds if some of their effects are corrected).

But radar altimetry also makes it possible to measure the altitude of large inland bodies of water and rivers, which can complement existing hydrometric measurement networks, or even replace certain gauging stations considered to be unreliable or inefficient (e.g. because of excessively long data delivery times). Satellite-based altimetry measures the level of rivers and lakes, according to a single reference level, ensuring global coverage for long periods, with no human intervention in the field apart from calibration activities.

## Altimetry today: measuring surface height

Satellite radar altimetry has been providing measurements continuously since the early 1990s, with two successive satellite families since then (the ERS-1, ERS-2, Envisat and Saral series, and the Topex/Poseidon, Jason-1, 2 and 3 series). A few other satellites were launched during this period (GFO, HY-2A and especially Cryosat-2). Some satellites were launched even before that date (Seasat, Geosat), but are not used in hydrology. Sentinel-3 is a new series in a new orbit, designed for long-term use; the first satellite (3A) was launched in February 2016.



*The history of altimetry missions*

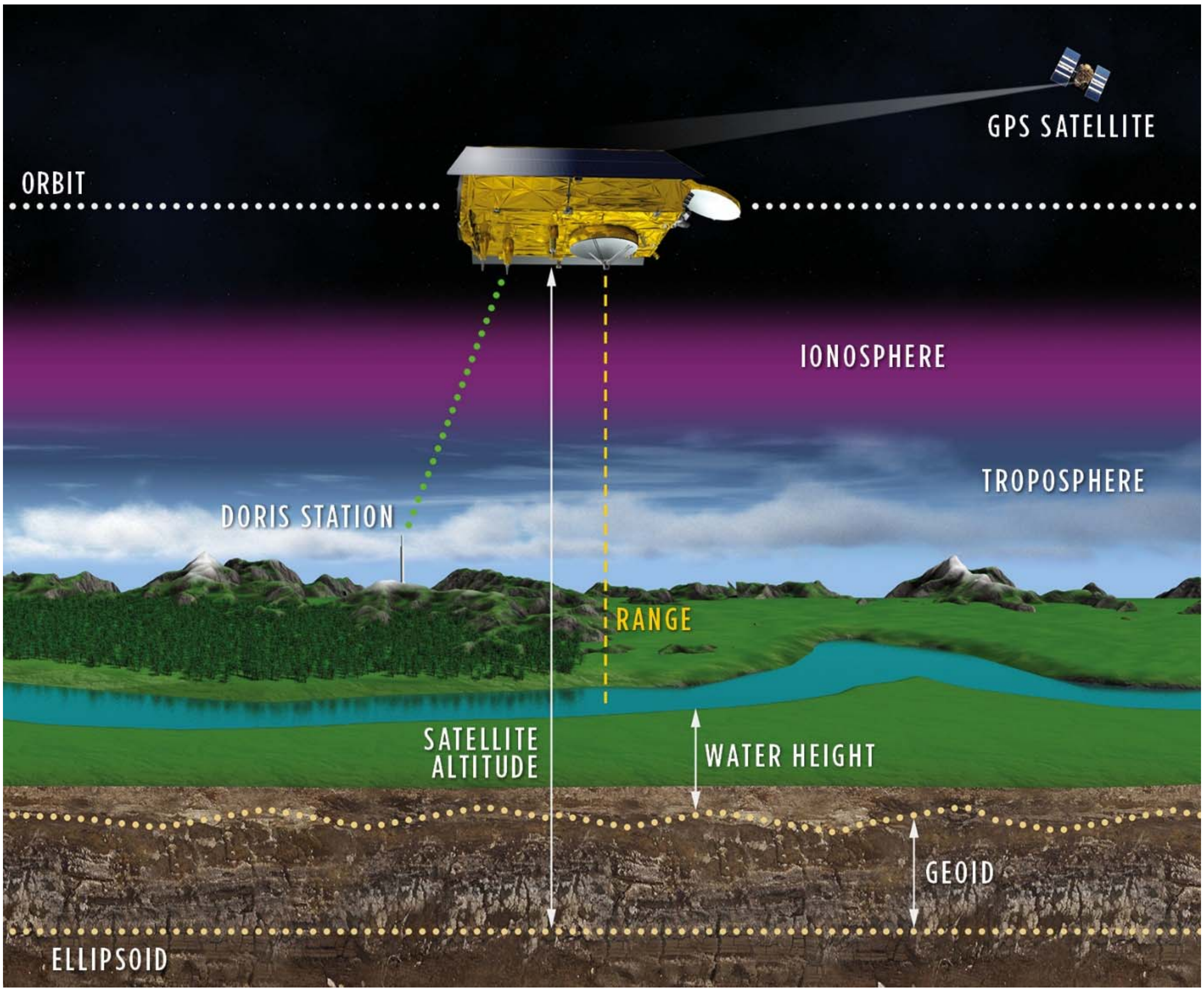
At present, all altimetry missions take measurements only at nadir (vertically below the satellite), and therefore provide observations with very limited spatial coverage. This is the main limitation of these missions.

Two techniques are currently used: "conventional" altimetry on the Topex/Poseidon, Jason, Saral or Envisat missions, known as Low Resolution Mode (LRM), and Synthetic Aperture Radar (SAR) also known as Delay-Doppler Altimetry, which is used on Cryosat-2 and Sentinel-3.

An instrument designed for wide-swath altimetry, a new technique, will be carried on the SWOT satellite to be launched in 2021 and will enable two-dimensional observation of rivers and water bodies.

To simplify, these two techniques use a radar wave emitted by the satellite vertically to the ground, which is reflected on the surface (water being the best “mirror”, at least when calm). We measure the round-trip time taken by the wave between the satellite and the surface; since we know the propagation speed of this wave (the speed of light) we can deduce the distance between the satellite and the surface. The principle is similar to that of sound wave reflection. When you shout in the direction of an object that can reflect (or bounce back) the sound of your voice, as when you are in a canyon or a cave, you hear the echo of your voice. If you know the speed of sound in air, you can then estimate the distance from the time required for the sound to make the round trip (by analogy, we also use the word “echo” in radar).

In addition, thanks to several payload instruments (Doris, GPS, laser reflector), we are able to determine the altitude and position of satellites very accurately. By subtraction, we can deduce the surface height relative to a reference level, and especially, by comparing one pass of the satellite with the next above the same point, we can observe variations in this height. The reference used in the basic data is an ellipsoid, a geometric shape which is a sphere flattened at the poles, similar to the shape of the Earth. In hydrology, however, the geoid is more frequently used, with equal gravity over its entire surface (i.e. a shape tracing an equipotential gravity field), closer to the actual shape of the Earth, since it is distorted by surface topography. This surface is generally given in the altimetry data, but other data give a more accurate value. The use of such a reference level makes it possible to obtain the altitude of the water surface, and therefore the slope, a key variable for hydrology.



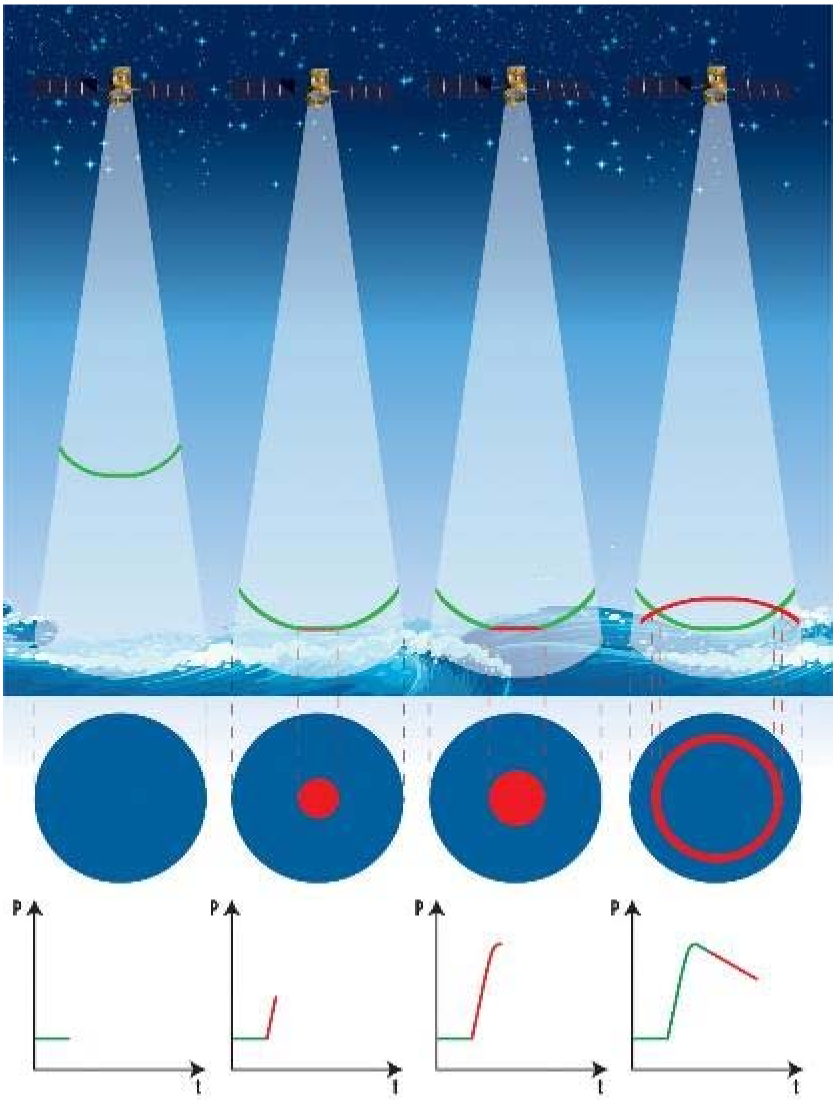
*The principle of altimetry*

However, this is only a simplified diagram. For one thing, it is necessary to take into account a certain number of factors that influence the speed of the wave, and to correct it accordingly, which is done via models (meteorological models in particular), and possibly via auxiliary measurements carried out by instruments on the satellite (or from models or other satellites) but especially over oceans. For another, we do not really time this round trip. This is because the reflective surface is rarely perfectly flat, and the wave has a spread ("ground footprint"), and a duration. All this means that the return echo does not arrive instantly at a given moment, but spreads over time with varying amplitude. We therefore work on the shape of the radar echo as a function of time, called its "waveform" in altimetry.

## Radar echoes in conventional altimetry

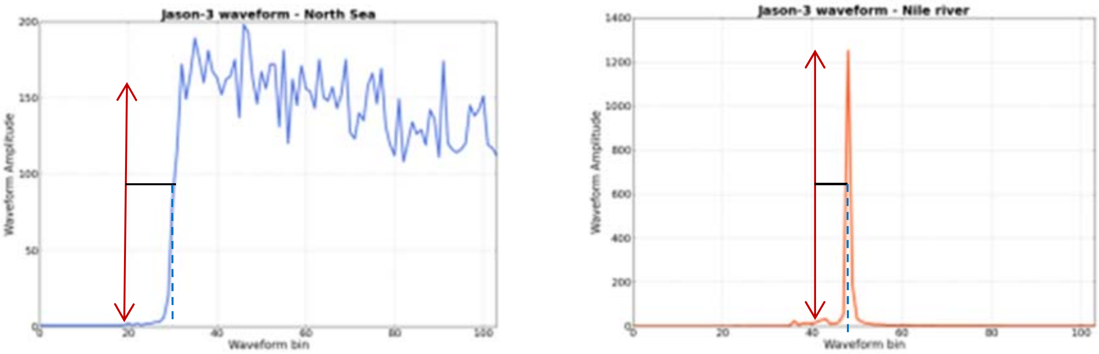
The satellites concerned are: ERS-1 & 2, Topex/Poseidon, GFO, Jason-1, Envisat, Jason-2, Saral, HY-2, and Jason-3 (as well as the precursor missions).

"Conventional" altimetry takes into account the reflection of the emitted beam as a whole – or at least, the part that returns to the satellite antenna.



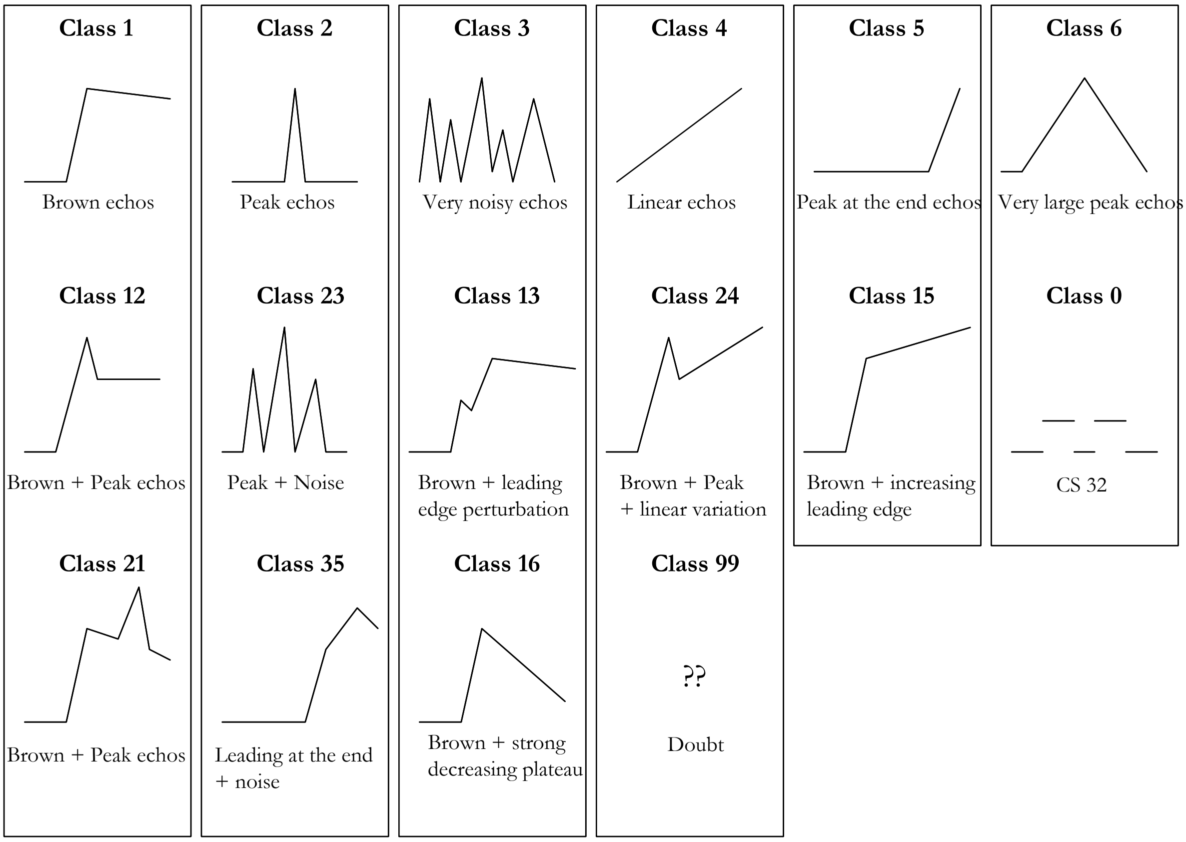
*Conventional altimetry echo on the ocean. At the top, a representation of the satellite and the emitted wave, with the reflected wave in red. In the middle, what happens on the surface (here the ocean has a flat surface). At the bottom, the echo (or waveform) received by the altimeter, with the red part of the curve corresponding to the step illustrated in the previous diagram.*

*The part that rises abruptly from this echo is used to determine the distance (the point at mid-height). The surface area of the red rings is the same as that of the circle; the downward slope of the curve depends on the gain of the altimeter antenna.*



*Conventional echo from an ocean (left), and from a river (right). Only the first is fully represented in the form of an equation [Brown, 1977]. From the second, however, we can extract time information using (in both cases) the time from the point halfway up the abrupt rise observed in both cases.*

Because of the diversity of echoes encountered on hydrological surfaces – single peaks or series of multiple peaks, more or less nested – classification studies have been undertaken as part of projects. The figure below illustrates the classes used for classifying Jason-2 data. Some classes consist of echoes from oceans or very large water surfaces (Class 1, Brown echoes). Echoes from rivers tend to be Class 2, or in classes with more noise (but therefore more difficult to use, such as Class 23, or even quite unusable, such as Class 3). Frozen lakes can return Class 13 echoes.



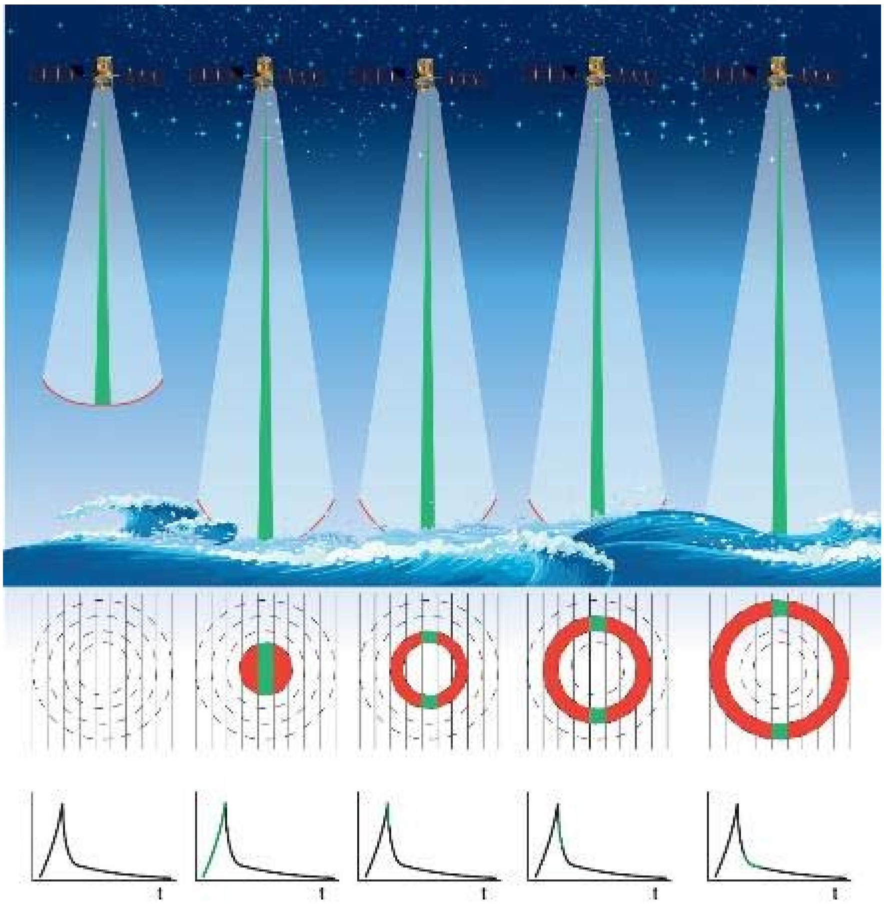
*Different echo forms (waveform classes, conventional altimetry); Class 2 is typically found for simple water courses, Class 1 ("Brown") being the classic waveform over the ocean.*

## Radar echoes in delay-Doppler altimetry

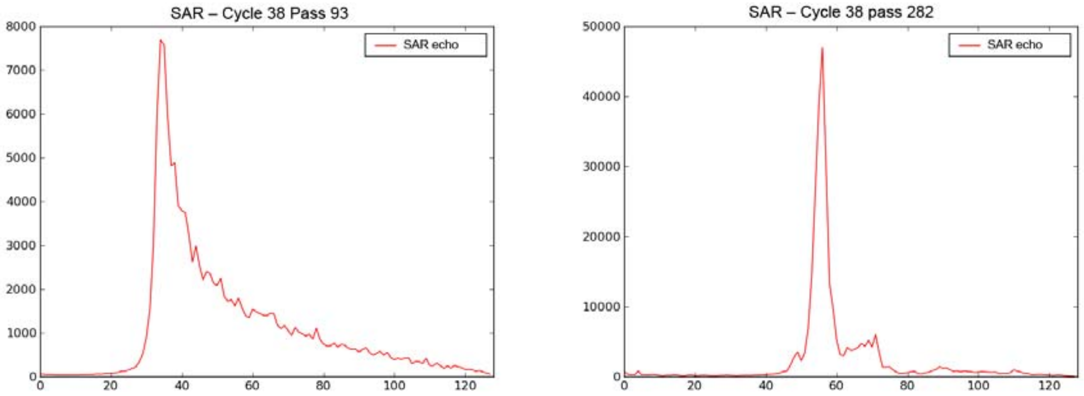
The satellites concerned are: currently Cryosat-2 and Sentinel-3 (A & B), and in the future Sentinel-3 (C & D) and Jason-CS/Sentinel-6.

The sound emitted by a moving object seems comparatively high-pitched, depending on the speed at which it approaches, or comparatively low-pitched, depending on the speed at which it moves away. This is called the Doppler effect (or Doppler-Fizeau effect when talking about electromagnetic radiation).

SAR altimetry uses this Doppler effect to distinguish between reflections from behind and in front of the transmitted beam: if they come from behind, it is as though the satellite were moving away, if they come from the front, the satellite is moving towards the target point. We obtain a series of "slices" of the conventional footprint, perpendicular to the satellite trajectory. And therefore, higher spatial resolution, at least in the direction in which the satellite is moving.



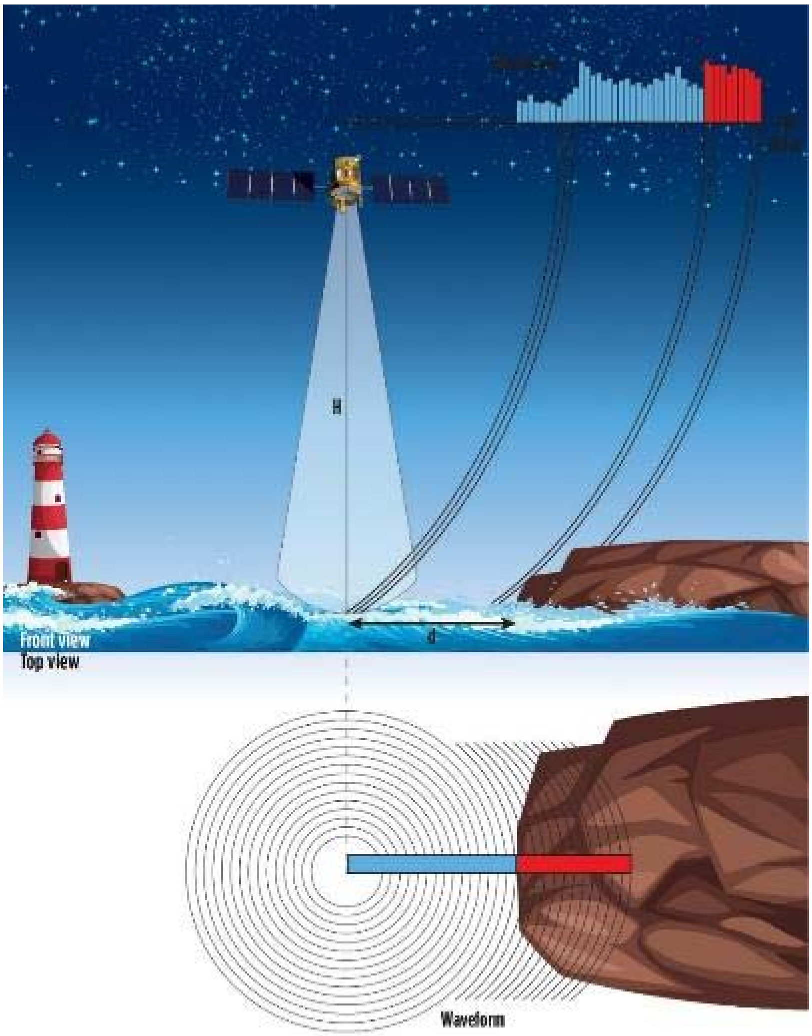
*Formation of an echo by Doppler altimetry (over the ocean); where conventional altimetry showed a near-plateau after the rise (because the surface area of each of the rings represented is equal), the echo in Doppler altimetry decreases. (Credits: CNES/CLS, from a presentation by K. Rayney)*



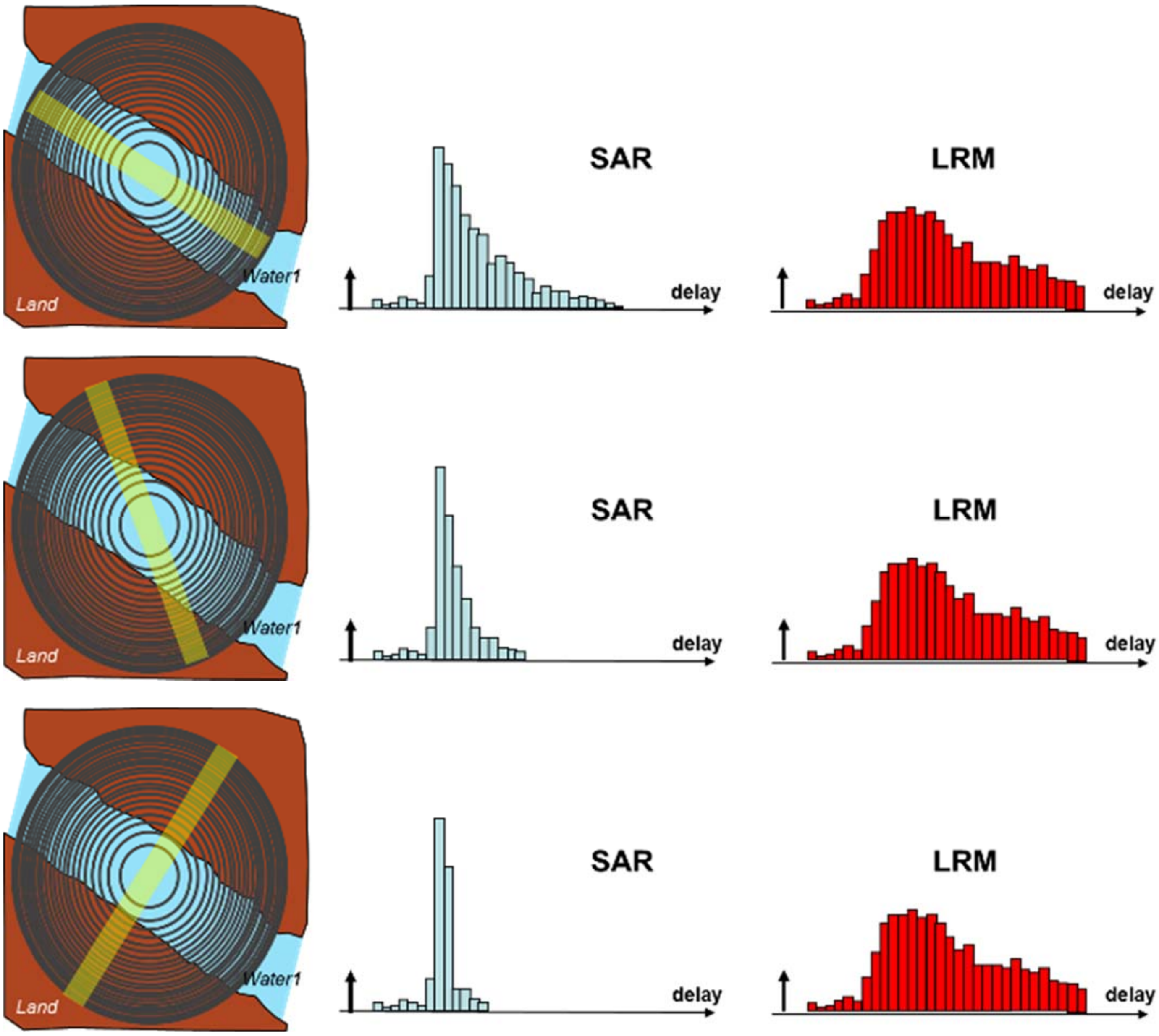
*Doppler altimetry echo from an ocean (left), and from a river (right).*

## What is the altimeter's radar wave reflected from? (or: What are we really observing?)

The “footprint” (or ground spot), i.e. the area from which the radar wave was reflected back to the altimeter, depends on the altitude of the satellite (723, 790 or 1336 km), the resolution of the waveform gate (related to the altimeter bandwidth), the aperture and gain of the antenna, and the duration of the measurement (or the number of “gates”). The radius can therefore vary from 4.8 to 9.5 km. This leads to surface areas of nearly 290 km² for Jason (at an altitude of 1336 km) and 100 km² for Saral. With the delay-Doppler technique, by which this surface can be divided into several “slices”, the observed area is greatly reduced but is still nearly 5 km². When looking at rivers and even small lakes, these areas will almost certainly include some land or vegetation cover. That said, if we only consider the rising edge and the first echo gates, we limit this surface a little, but some information may be lost.



*The presence of land in the footprint can perturb the echo; the more reflective the land, the stronger this perturbation will be.*



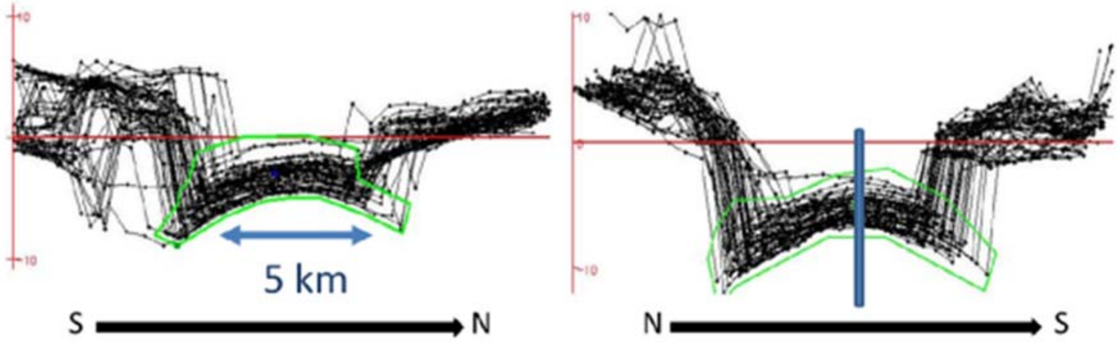
*Echoes in SAR or conventional (LRM) modes according to the respective positions of the satellite trajectory (perpendicular to the rectangles of the SAR mode) and the watercourse.*

The conditions for acquiring altimetry measurements on large lakes and inland seas are very similar to ocean conditions. If the water surface areas are large enough, and if we place ourselves far enough from the banks and the surrounding land forms, we mainly obtain so-called “Brown” echoes.

Over rivers, the signal is more complex due to the heterogeneity of the surfaces observed. The signal is reflected back from a mixture of surfaces of different types and degrees of reflectivity, such as open water, forests, floodplains, etc. This significantly affects the shape of the echo (e.g. echoes with multiple peaks), and consequently on the ability to extract the required information, especially range, resulting in less accurate measurements. All altimetry data from heterogeneous surfaces must be reprocessed to produce a sufficiently accurate measurement of surface height. This reprocessing is called “retracking” and uses specific algorithms (Ice1, Ice3, SeaIce, etc.). It can be refined by using different algorithms depending on the type of waveform, which can also limit the area considered in the observation by taking only the beginning of the echo (the first “gates”).

These retracking algorithms are based on empirical approaches, because there is no analytical model apart from that for the open ocean (the Brown model). Research is under way to improve these algorithms. One approach currently being developed uses a digital terrain model (DTM) and roughness maps (Legos). Another analyses the waveforms preceding and following the one being processed (Legos/Ifremer), on the principle that they should be similar.

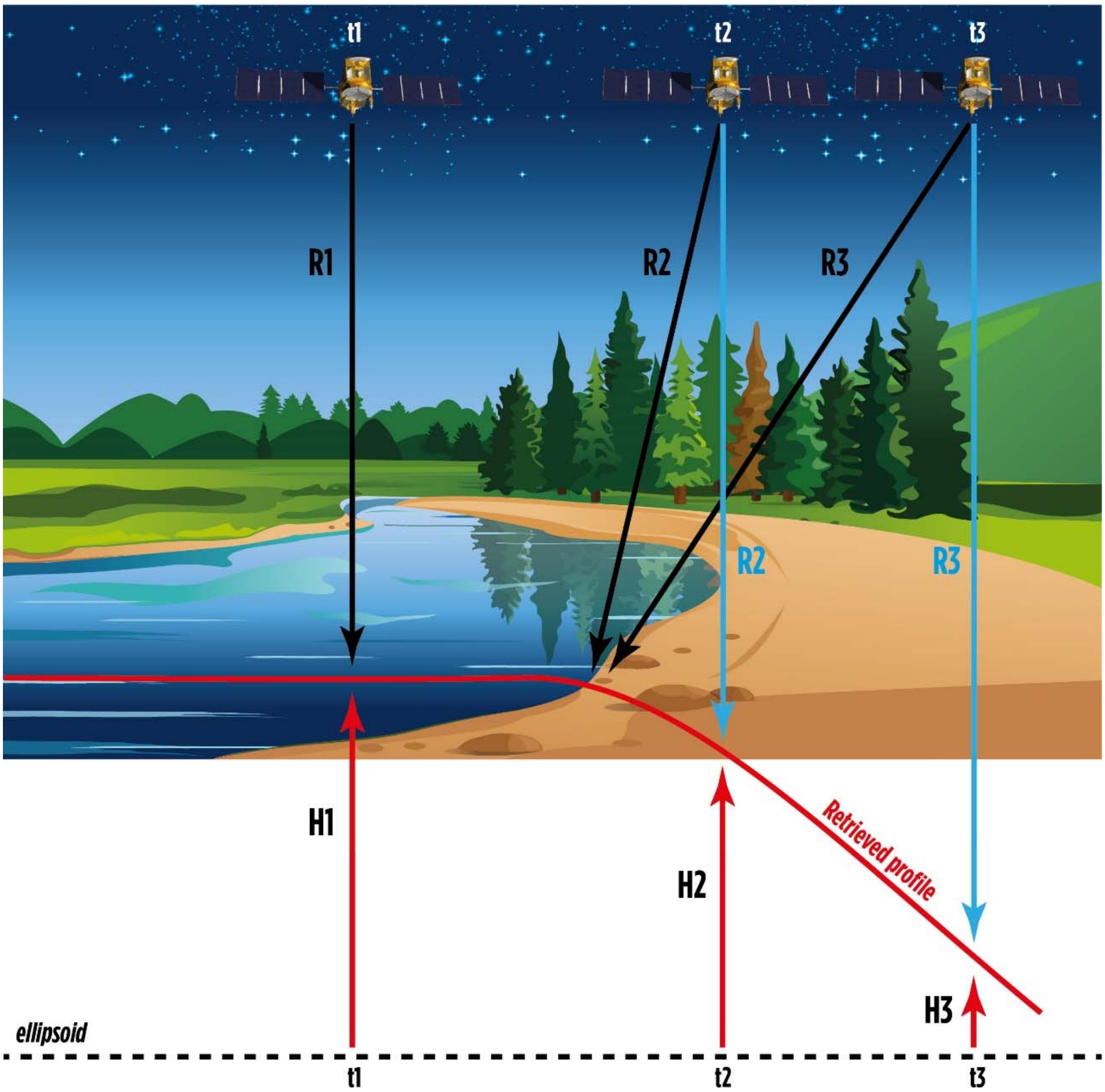
In addition, reflections are sometimes observed on slightly sloping and highly reflective surfaces (e.g. a wet sandy beach), such as along the banks of the water surface, which reflect the radar wave. The altimeter then receives an "interference" signal that does not reflect the water level (or even the bank level, because it does not come from nadir).



*Example of persistent hooking on the Rio Paro (Credits: S. Calmant, IRD)*

Hydrological profiles of lakes, rivers and floodplains, obtained by satellite altimetry, are expected to be flat or slightly inclined due to the slope of the body of water. However, upwardly-facing parabolic structures are observed on many hydrological profiles. This artefact, known as *hooking*, occurs when the altimeter continues to measure a reflective surface it has just flown over despite no longer being above it, resulting in a longer round-trip time for the wave, leading to an underestimation of the surface height measured by the altimeter (overestimation of the satellite-to-surface distance). When such parabolas are detected it is possible to apply a geometric correction, and to increase the number of observations of the watercourse, thus reducing the uncertainty associated with the measurement. This is particularly useful for rivers whose narrow width limits the number of observations by the satellite (see the figure above, where the narrow river – blue bar – is sampled over several kilometres by means of hooking).

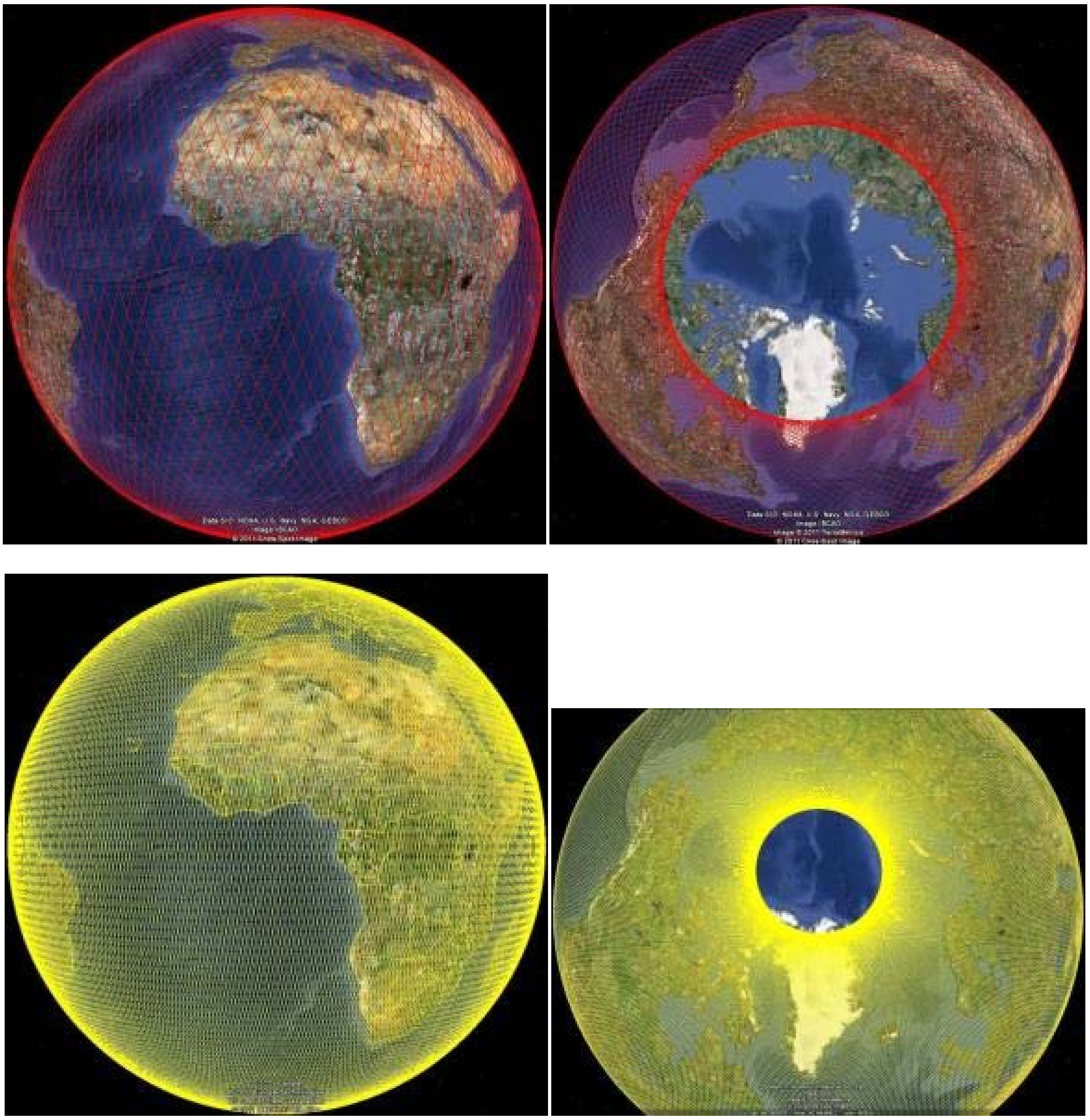
An average or median of the individual measurements of the body of water is used to eliminate random noise. Altimeter data are generally provided at two different resolutions, often in the same file; one, called "1 Hz", provides a measurement average per second. The other, whose frequency depends on the satellite (10, 20 or 40 Hz), is only averaged over 1/10th, 1/20th or 1/40th of a second, thus providing closer but noisier measurements. This corresponds to measurements about every 700 m (Topex/Poseidon), 350 metres (Envisat, Jason, etc.) and 175 metres (Saral) respectively.



*Schematic diagram of persistent hooking; observing "from an angle" increases the measured distance, resulting in a misperceived surface height.*

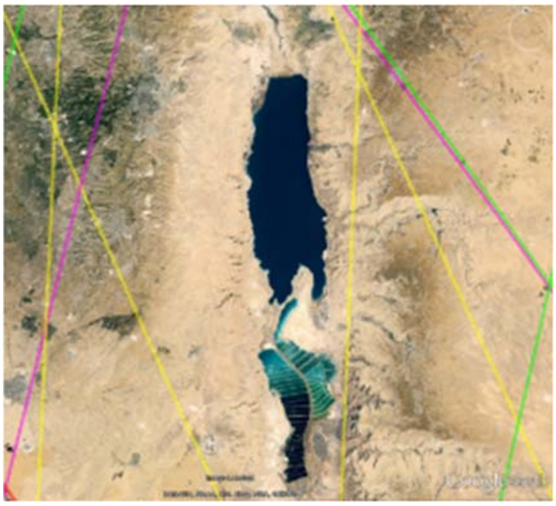
## Spatial and temporal coverage of measurements

Current altimetry is not imagery: the satellite "probes" what is directly below it. In addition, the choice of altimetry satellite orbit is a trade-off between spatial and temporal sampling: if a satellite frequently passes over the same point (high temporal sampling), it will cover less territory than if it has a longer orbital period (smaller temporal sampling).



*Ground tracks for Jason (top) and Saral (bottom). The mesh size is much wider for the Jason mission, and the measurements further from the poles, but the revisit interval is 10 days, which means that we can observe variations in hydrological phenomena in finer temporal detail.*

This results in a very different mesh sizes, but which never cover the entire surface. Some large bodies of water may not be observed at all by certain satellites, such as the Dead Sea or Lake Hourtin (Gironde, France).



*The tracks of Jason-1, Envisat and GFO around the Dead Sea.*

One way of overcoming this problem is to combine several satellites. From this point of view, the strategies implemented over more than twenty years of associating satellites with the same orbits with revisit times of 10 days, 35 days and longer introduces the possibility of processing the data in archives for three generations of satellite combinations (Topex/Poseidon/ERS-1 & 2, Jason-1/Envisat, and Jason-2/Saral) for hydrological purposes. Jason-3 and Sentinel-3A (and soon Sentinel-3B) are now expected to provide a unique spatio-temporal coverage, which will be prolonged for the next decade (Jason-CS, Sentinel-3C & D).

*Ground tracks of the Sentinel-3A & 3B satellites, again over the Dead Sea*

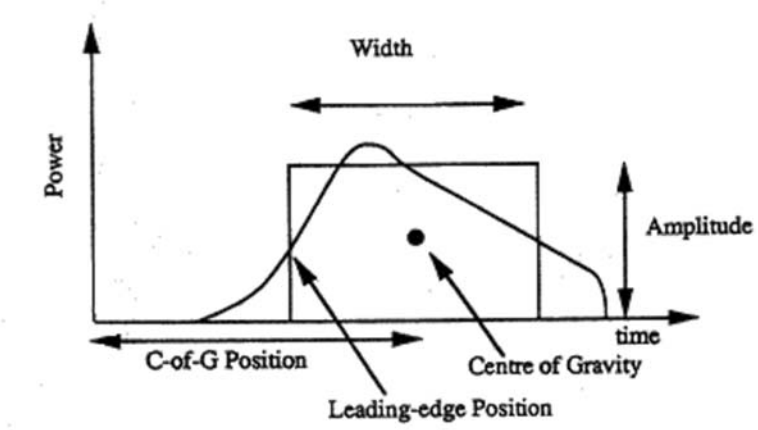
Another approach for rivers is to model what happens downstream of the satellite measurements. Satellite altimetry measurements are used as if a gauging station were installed at the point where the ground track crosses the watercourse, coupled with meteorological data, to model what happens downstream. The contribution of altimetry observations is particularly significant in the case of watersheds that cross national frontiers, where it provides downstream countries with information on the status of hydrological variables in the upstream parts of the watersheds.

However, the low sampling frequency makes the direct use of altimetry measurements unsuitable for early warning of floods. They can however be used for early warnings further downstream (http://floodlist.com/asia/bangladesh-expand-servir-satellite-flood-warning-system) and also afterwards to understand and model such events.

## From the echo to the water surface height

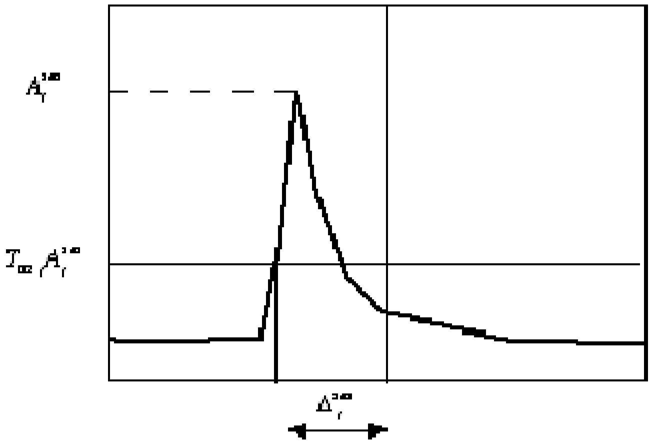
As mentioned above, the satellite-to-surface range is deduced from the radar echo. On a typical “ocean” echo (or that from a large lake), we base this estimate on the abscissa of the point at mid-height of the steeply sloping part (the rising edge; we determine the distance in relation to half the wave height). In more complex cases, for example when several “peaks” occur, as is frequently found in inland waters, the situation is more complex, and retracking algorithms are used to estimate this range.

- ☐ Algorithms based on a threshold method:
    - Ice1 (Wingham et al., 1986): originally developed for the study of polar ice caps. The principle is to define a rectangle whose centre of gravity matches that of the waveform. We then take the abscissa of the first point whose power reaches a given percentage of the amplitude of this centre of gravity (30% in this case);



*Principle of the Ice1 algorithm (after Wingham et al., 1986)*

- Ice3 works on the same principle as Ice1, but only analyses a limited part of the waveform (the end of the echo is ignored);
- Sea-Ice (Laxon, 1994): algorithm used to study sea ice.

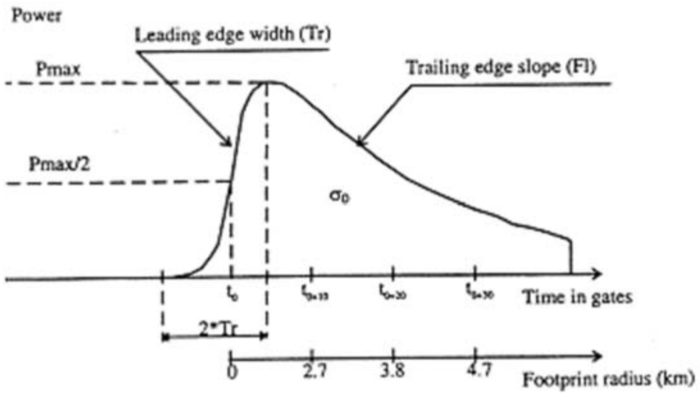


*Principle of the Sea-Ice algorithm (Laxon, 1994)*

These three retracking approaches are empirical (and not based on physical laws formulated mathematically); they do not take into account the characteristics of each instrument, and only provide the satellite-surface range and backscatter coefficient, not the other parameters that can be extracted from the echoes. Ice1 is the one most frequently used in hydrological applications. Ice3 improves these results, but has only been tested on Jason-2.

□ Algorithm based on the adjustment of real waveforms to theoretical waveform models:

- Ocean [Brown, 1977]: basic algorithm used since the first altimetry missions. A Maximum Likelihood Estimation (MLE) algorithm is used, which is based on three or even four parameters (MLE3 or MLE4);
- Ice2 [Legrésy and Remy, 1997]: created for the study of the polar ice cap of Antarctica and the Greenland ice sheet;



*Theoretical waveform sought by Ice2*

- Red3 analyses only part of the echo (-10 ; +20 samples with respect to the rising edge) with a maximum likelihood estimator (resolved with three parameters: range, amplitude and composite Sigma);
- Oce3 works on the principle of maximum likelihood with three parameters (MLE3), but on a previously filtered echo to reduce noise.

With the exception of Ice2, these methods are most suitable for the ocean, and possibly for large lakes or water bodies.

- Pattern recognition method: waveforms are sorted according to their appearance; a reprocessing algorithm adapted to each identified type is then applied;
- The Adaptive Retracker combines several improvements tested in different projects. It uses a surface roughness parameter enabling different types of surface to be taken into account. It adapts its analysis to the useful length of the echo, according to each class. It also takes into account the actual impulse response of the instrument, not a theoretical impulse. This enables us to get as close as possible to the waveform, regardless of the surface the wave is reflected back from, without using different algorithms, while providing as output all the parameters that can be extracted from the echoes (satellite-surface range, but also slope of the rising edge and amplitude, slope of the trailing edge).

## From surface height to hydrographic variables

A satellite altimeter does not generally follow a river along its entire course, but crosses it from time to time; we therefore define the concept of a “virtual station”. It is as though we had a stream gauge located at the average of all the points where the satellite crosses the river. This measurement can then be used as an *in situ* measurement, except that the depth of the watercourse at this point is not necessarily known precisely; we therefore work more on variations in surface height than on depth (absolute height from the bottom of the river bed). Compared to conventional *in situ* databases, satellite altimetry provides observations at a higher spatial resolution (even if the possible observation points are predetermined by the chosen orbit, there are more of these than there are *in situ* stations) but at a lower temporal resolution. However, in many cases, *in situ* databases are only updated periodically, and the only information available in near-real time is therefore from satellite observations.

Height measurements can be combined with optical or radar images obtained by other satellites (the different Spot and Pleiades satellites as well as Sentinel-3, Sentinel-2, Sentinel-1, CosmoSkyMed, TerraSAR, etc.) to determine the extent of a body of water. This is how changes in water volume are calculated.

In addition, the flow rate of a watercourse can be calculated from the height, combined with other information. Models of different degrees of complexity, incorporating different amounts of auxiliary information (bathymetry, etc.) have been developed (height/flow rating curves, hydraulic models, assimilation methods, etc.). The methods are generally based on the existence of a clear relationship between the variation in height and the variation in flow. Recent studies, covering many river basins around the world, have shown that it is possible to obtain flows from water levels. Improving these techniques is one of the important tasks involved in preparing the SWOT mission. The coupling of meteorology with altimetry holds out good prospects for knowledge of flow.

## What degree of accuracy?

The accuracy of altimetry measurements in hydrology depends considerably on the body of water to be observed and its close environment. The geometry of the ground track in relation to the water, the banks and their topography, vegetation, etc., must all be taken into account.

Several factors affect the accuracy of altimetry measurements over inland waters. Environmental corrections are one of the possible causes of error. The uncertainties induced by the width of the radar beam are even more important. Since it is several kilometres across, most of the echoes come from a mixture of water, islands and banks (if they are flat). These mixtures, as well as the nadir echoes from smooth bodies of water, which are highly reflective, make it difficult to determine surface height using the algorithms currently available. The results obtained with any of these depend on the environment of the virtual station (vegetation, surrounding topography, bed type, steep or flat banks, etc.). In addition, experience shows that the biases affecting a virtual station also affect a sensor (or mission).

The satellite-surface range is estimated to within 2 centimetres over the oceans. This can be about 5 cm over large lakes (any large surface of water “perceived” by the altimeter as an ocean). Over rivers, the accuracy for conventional altimeters is usually no better than 15 to 20 cm for the best virtual stations (those with the best radiometric contrast), and can be as much as 60 to 80 cm for the least accurate virtual stations. The first studies into the efficacy of SAR and InSAR technologies have shown that they give better results than conventional altimetry, but they still depend on a large number of factors related to the river and its environment.

Finally, it should be noted that altimetry data are made available with different delays following the measurement. The fastest time is 2 hours, then 24 to 48 hours and finally 30 to 75 days. These additional delays are to enable the collection of auxiliary data (for meteorological models in particular), but above all to calculate the altitude more precisely because, by waiting longer, we learn more about the trajectory of the satellite on its orbit, which enables more precise calculations. On water surfaces, the improvement between the data received after 24/48 hours and the data received after 30 days is not necessarily significant. Consequently, the choice between these types of data depends on the type of use desired, between operational use (which implies rapid data delivery), and a long-term study (where only data with the longest delay will be available over the lifetime of a satellite).

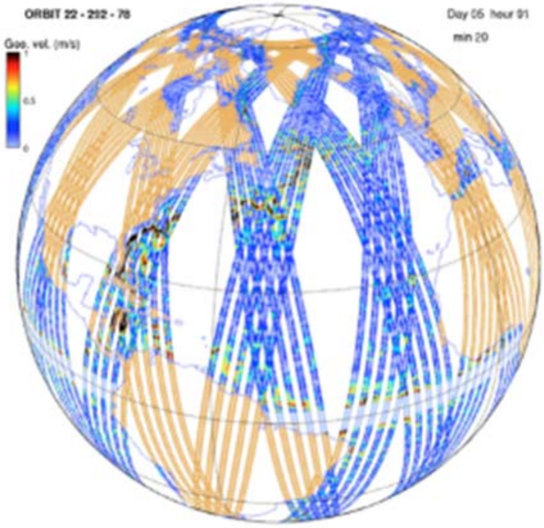
## The data available

In conventional altimetry for hydrology, there are two main categories of data available:

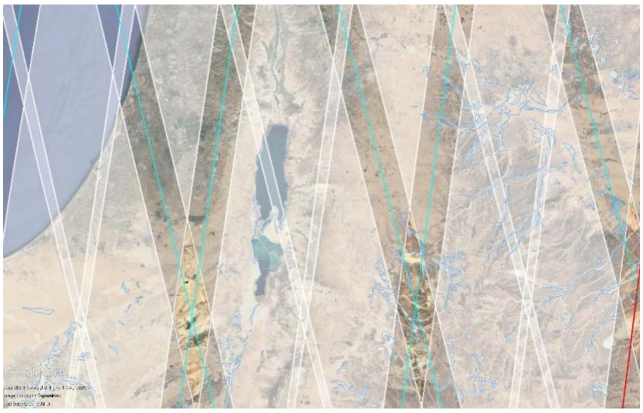
- Data from Geophysical Data Records (GDR) and from Sensor Geophysical Data Records, which contain all the elements necessary for calculating a water level every second and every 1/20th of a second along the track of each satellite; today these data are provided in a self-described and standardised NetCDF format (although this is not yet the case for all data from the 1990s). There are also variants containing very recent algorithms, which may be more interesting for hydrology. These data are complete, but quite complex to use.
- “Pre-calculated” water level data on selected rivers and lakes, often provided in text format (including csv). They are much simpler to use, but are not calculated everywhere. Open access and free of charge, these databases aim to catalogue the satellite water levels of as many rivers as possible in order to offer various users (governments, research institutes, design offices, etc.) the possibility of monitoring water resources (e. g. hydroweb.theia-land.fr).

## Tomorrow, with SWOT

The future SWOT altimetry mission (for Surface Water and Ocean Topography, NASA/CNES/CSA/UKSA) will be profoundly different from previous ones. SWOT will not only provide height measurements, but will also be able to estimate widths or expanses of bodies of water. In addition, the data will be in the form of an image: a grid of measurements extending over two 50 km swaths on either side of a 20 km swath, in the middle of which only the traditional nadir measurement will be performed. In addition to the advantage of obtaining two-dimensional data and therefore slopes in all directions, this will also make it possible to cover almost the entire surface of the globe, without the gaps in the grid left by previous satellites – or almost.



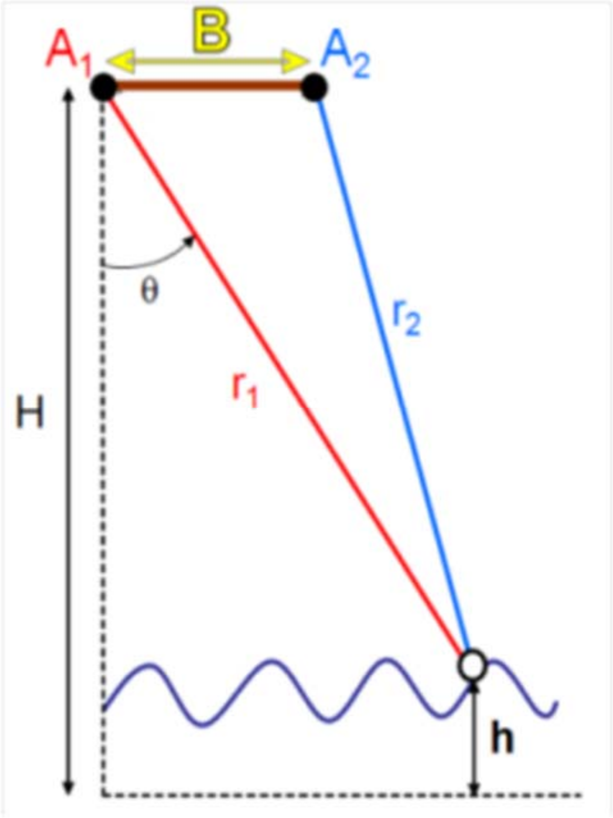
*SWOT ground tracks over 5 days (out of 22 of the complete cycle)*



*SWOT ground tracks zooming in on land*

The satellite will have two antennas, one on either side of the main module. They will operate on the principle of interferometric synthetic aperture radar (InSAR), but will emit much closer to nadir than other instruments of this type, between 0 and 4° (as opposed to 30° in general). As in “SAR mode” or “delay-Doppler” altimeters, the position of each point on the surface on which the reflection is made is deduced from the Doppler effect.

The radar wave will be transmitted from only one of the two antennas, alternately first towards its own swath on the ground and then to that of the other antenna. Both of the antennas will receive the wave reflected back from the surface. Differences in range can be measured from the phase difference between these two waves.



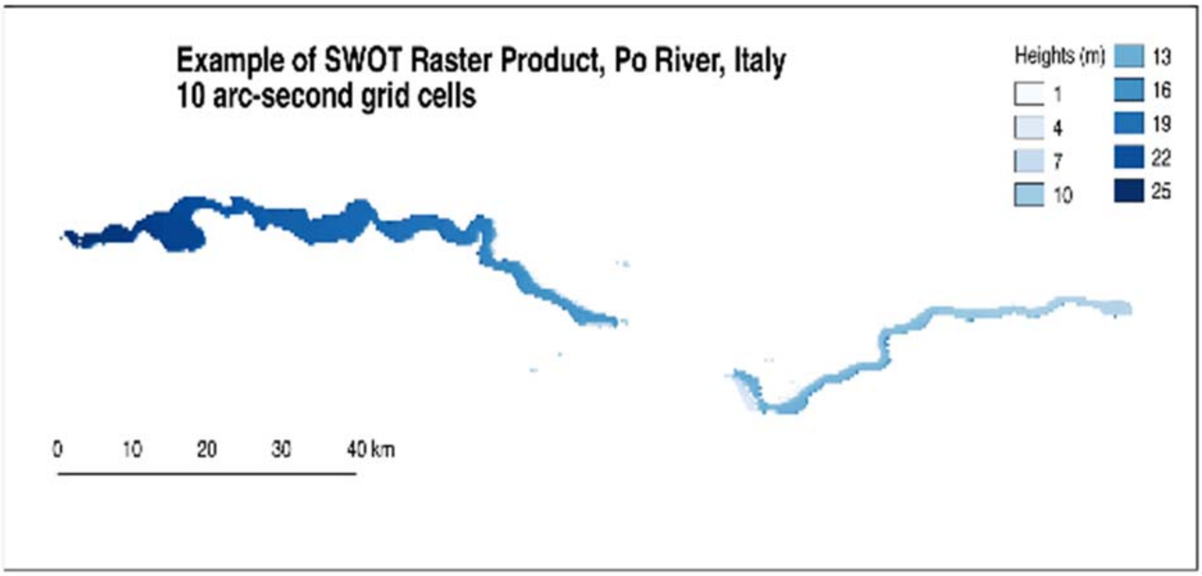
**A1 and A2 each represent an antenna. B is the distance between the two, fixed and known;**

**r1 is measured as in conventional altimetry, by round-trip time, and H is known from an orbit-determination system.**

**In addition, the angle $\vartheta$ is deduced by measuring the phase difference between the two waves received by each antenna, based on the interference between these waves. However, by definition, this phase is only known to the nearest $2\pi$. Knowledge of the mean topography (DTM) will help remove this ambiguity.**

**Once all these quantities are known, we deduce h: $h = H - r1 \cos(\vartheta)$**

The objective for SWOT by 2021 is accuracy of less than 10 cm over an area of 1 km$^2$, for an elementary resolution of 5 m (along the track) x 10 or 70 m (across the track) over land.



*SWOT data simulated on a river: example of the Po (Italy)*

## Hydrological products provided by SWOT

Four main products have been defined. The rawest is in NetCDF format, while the other three are in shapefile format, compatible with GISs. River- and lake-specific products are linked to *a priori* databases, which will be updated during the mission.

### *"River" products*

Each river over 30 m wide is defined in an *a priori* database, either as a line along the centre of the river divided into sections about 10 km long, or as nodes every 200 m along this line.

River products are provided according to these two types of breakdown, as defined in the *a priori* database: for the "node" product, with mean values around each node for parameters such as width, height, flooded area, etc., and for the "section" product the mean height, mean slope, mean flow, etc. on each of these river sections.
These products are provided for each satellite pass.
The "section" product is also provided by cycle, in which case the values of the variables are provided on each of the different passes that measured all or part of the section of the river in question during an entire satellite cycle (21 days).

*Definition of a river section*

*Definition of river nodes*

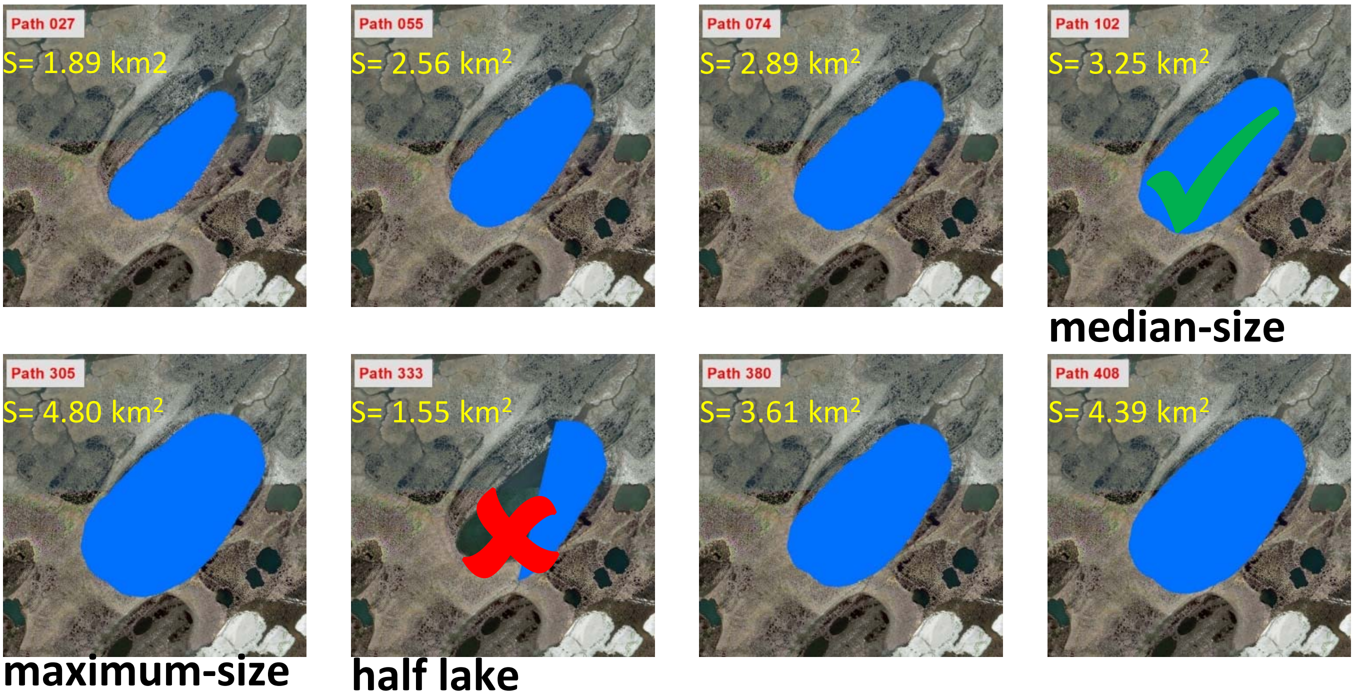
### *“Lake” products*

Water surfaces that are not known rivers, and that are more than one hectare in size, are treated as “lakes”.

The product for each individual satellite pass gives information (height, surface area, contour, etc.) for each observation of these surfaces.

For each object that can be linked to an element of the *a priori* lakes database, the identification information is added.

The product for each cycle includes a median contour, and the average height of the lakes for passes when they were seen in their entirety (observations of only part of the lake are not taken into account). Other more complex scenarios (views of different parts of the lake at each passage) will be taken into account.

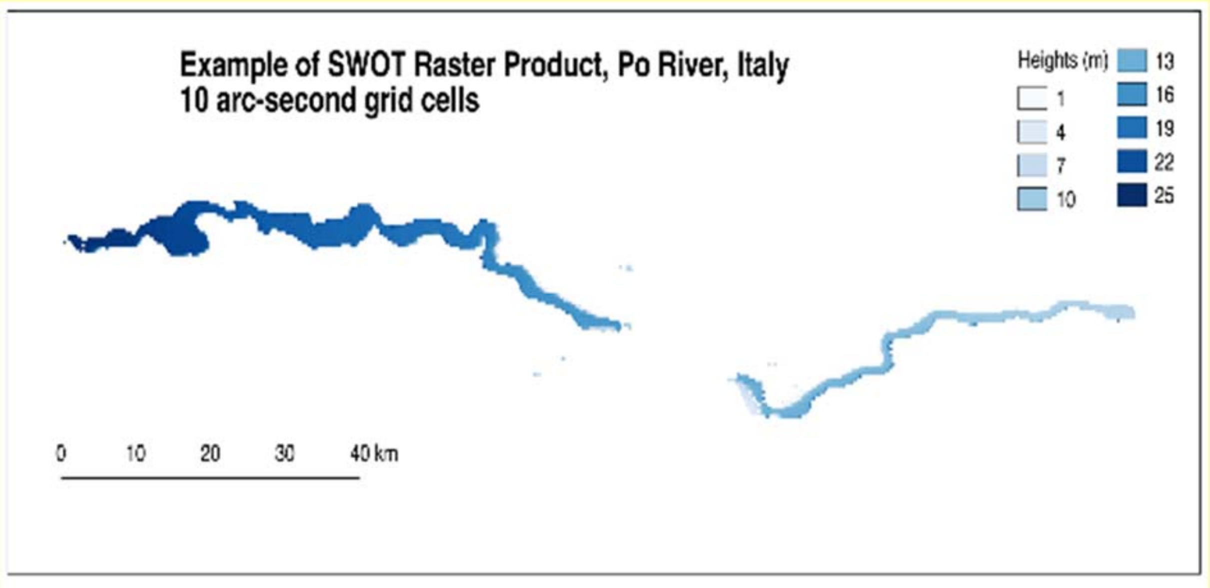


*Multi-temporal, median-size composite scheme applied:*

*max area: 4.80 km2, min area: 1.89 km2, stdev. area: 0.94 km2, med area: 3.25 km2.*

*Illustration of the definition of the contours of a lake (Figure courtesy of Y. Sheng)*

### *“Raster” products*



*SWOT data simulated for a river: example of the Po (Italy)*

A “raster” product (see the example of the Po above) will be systematically generated from the “pixel cloud” product. It will be in NetCDF 2D format, will cover four point-cloud tiles (the 2 swaths and 120km along the ground track) and will come in two resolutions: 100m and 250m. The points of the pixel cloud will be plotted on a regular grid according to a Universal Transverse Mercator (UTM) projection. This will be a one-per-pass product.

It can also be generated on demand (via the data dissemination portal, TBC):

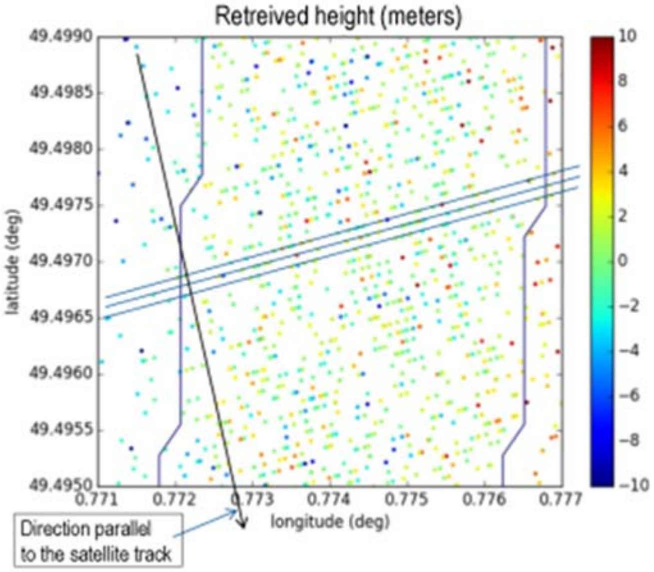
- format: NetCDF, GeoTiff, etc.,
- variables,
- resolution (>100m) and user-defined area, with a limit on the volume of the data to be downloaded.

### *“Pixel cloud” product*

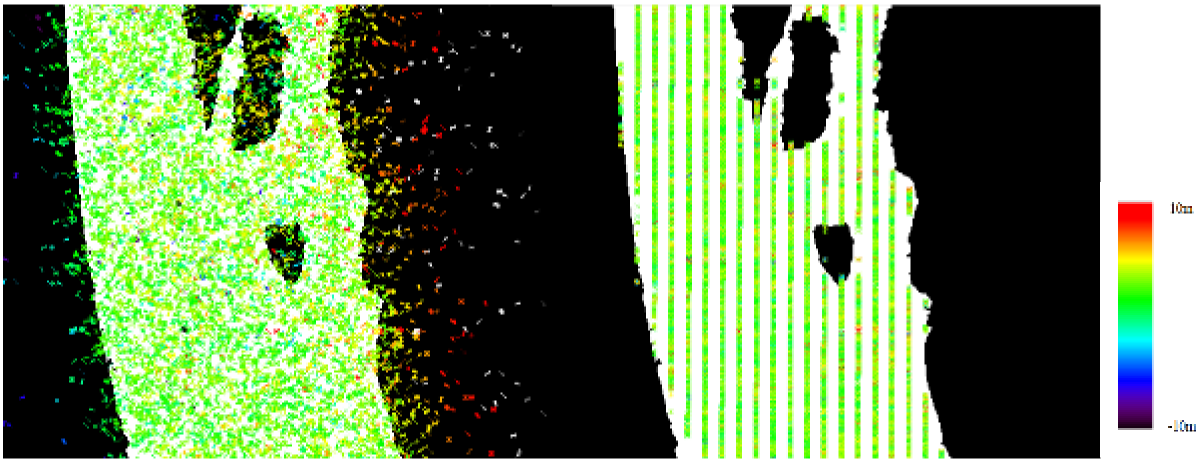
This is the rawest product for land surfaces. A file, in NetCDF format, covers a tile, which corresponds to a swath on one of the two sides (left or right) over 60 km along the satellite's ground track.

The product provides longitude, latitude, height, pixel size and corrections for each point classified as water, for points on a buffer zone around these water zones as well as on systematically included areas (defined according to an *a priori* mask).

This product is generated for each pass of the satellite.



Pixel cloud product on one of the swaths



*(Left: raw pixel cloud – Right: improved geolocation)*